

## SOFT X-RAY SOURCES AT THE CENTERS OF THE ELLIPTICAL GALAXIES NGC 4472 AND NGC 4649

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Analysis of recent *Chandra* observations of the elliptical galaxies NGC 4472 and NGC 4649 has revealed faint soft X-ray sources at their centers. The sources are located to within  $1''$  of the optical centers of the galaxies. They are most likely associated with the central supermassive black holes. Interest in these and several other similar objects stems from the unusually low luminosity of the supermassive black holes embedded in dense interstellar medium. Our *Chandra* sources have very soft spectra. They are detectable only below  $\sim 0.6$  keV and have luminosities in the 0.2–2.5 keV energy band of  $\sim 6 \times 10^{37}$  erg s<sup>−1</sup> and  $\sim 1.7 \times 10^{38}$  erg s<sup>−1</sup> in NGC 4649 and NGC 4472, respectively.

**Keywords:** elliptical galaxies — NGC 4472 — NGC 4649 — supermassive black holes — X-ray radiation — Chandra telescope.

### INTRODUCTION

Supermassive black holes with masses  $\sim 10^8 - 10^{10} M_\odot$  are suspected at the centers of many galaxies on the basis of the stellar dynamics in central galactic regions (see, e.g. Magorrian et al.1998; Gebhardt et al.2000; Kormendy and Richstone 1995). Being embedded in a dense medium, these objects must actively accrete the surrounding material, resulting in a considerable luminosity of the central galactic regions. Quasars, blazars, and radio galaxies are different manifestations of the activity of the central supermassive black holes.

The dilemma known for several years is that, despite the predicted high accretion rates on the supermassive black holes, the luminosities of the nuclei of many galaxies are many orders of magnitude lower than those predicted by standard disk accretion models. For instance, in the elliptical galaxies NGC 4472 and NGC 4649 discussed below, optical observations indicate the existence of black holes with masses  $\sim 3 \times 10^9 M_\odot$   $\sim 4 \times 10^9 M_\odot$  respectively (Magorrian et al.1998). The luminosity of the nuclei of these galaxies calculated using the formula of Bondi (1952) with a 10% efficiency of energy release of the total accreted mass and with the parameters of the interstellar medium derived below is  $\sim 5 \times 10^{44}$  erg s<sup>−1</sup> for NGC 4472 and  $\sim 7 \times 10^{44}$  erg s<sup>−1</sup> for NGC 4649. Actually, however, the luminosities of the nuclei of these galaxies are much lower (Loewenstein et al. 2001).

X-ray observations of NGC4472 and NGC4649 with ROSAT (Irwin and Sarazin 1996; Trinchieri et al.1997) and their optical observations with the Hubble Space Telescope found no evidence of activity of the central source. Radio observations (Condon et al 1991; Wrobel 1991) provide the

only evidence of the nuclear activity. They revealed radio sources at the centers of these galaxies and radio lobes in NGC 4472.

There are theoretical models that explain such low luminosity of the accreting black holes in galaxies with low-luminosity nuclei: the model with an advection-dominated accretion flow (Narayan and Yi 1995a,1995b; Abramowicz et al.1995) and the model with a convection-dominated accretion flow (Narayan and Yi 2000; Quataert and Gruzinov 2000). The strictest predictions of these models refer to the radio and X-ray ranges, in which the theory tested observationally (Di Matteo et al.1999). Therefore, of considerable interest are observations with *Chandra* whose superior spatial resolution helps to detect extremely faint point sources.

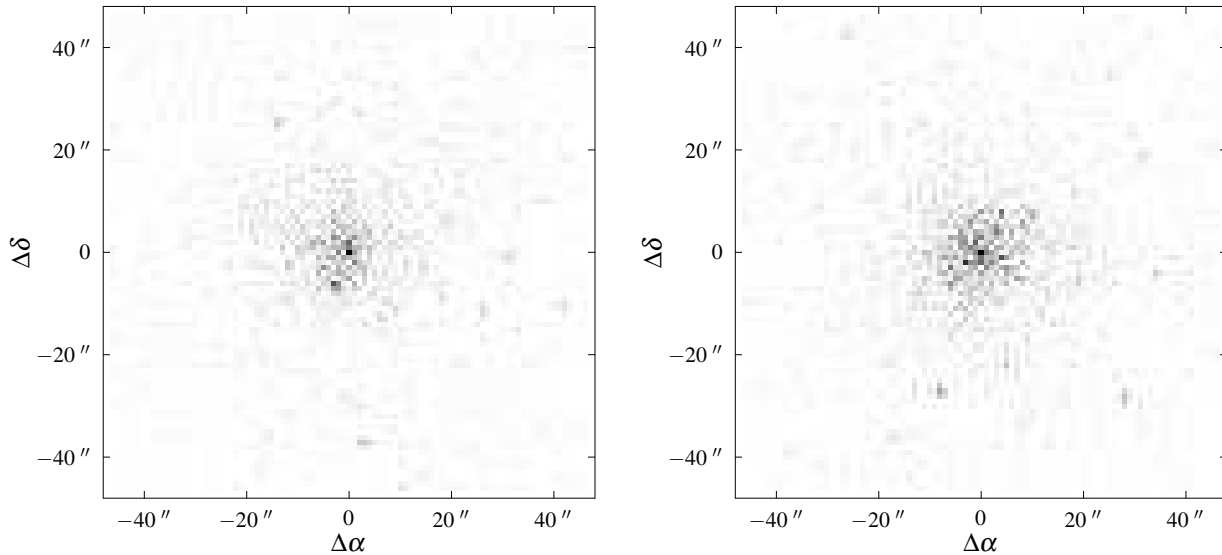
In this Paper, we analyze the archival Chandra observations of NGC 4472 and NGC 4649. We detect previously unreported faint, soft X-ray sources at the centers of both galaxies. The most plausible interpretation of the nature of these sources is activity of the central black hole. To our knowledge, this is the first X-ray detection of the “quiescent” supermassive black holes in elliptical galaxies.

### DATA ANALYSIS

We used the *Chandra* observation of NGC 4472 carried out on June 12, 2000, and of NGC 4649 on April 20, 2000, with a total exposure of  $\sim 40\,000$  s each. The ACIS S3 detector was used in both observations. The data were processed with the standard event filtering criteria and latest calibration data. We also corrected the ACIS S3 quantum efficiency for the contamination buildup on the optical blocking filter, which is particularly pronounced at energies below 1keV.<sup>1</sup> During the observations there were flares of the

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**Fig. 1.** Detector images of the galaxies NGC4472 (left) and NGC4649(right) in the range 0.2–0.6 keV. The image pixel size is 1''. The images are centered on the location of the optical peaks.

particle-induced background with a duration of  $\sim 7000$  s for NGC 4472 and  $\sim 8000$  s for NGC 4649. Since we are primarily interested in a small region in the central, bright part of the galaxies, we opted to keep the data from the flaring periods.

At low energies, the detector angular resolution degrades from 0.5'' to  $\sim 1''$ . Since one pixel on the ACIS S3 detector corresponds to 0.5'' faint soft X-ray sources are most noticeable when the image is blocked into 1'' pixels. The subsequent analysis was carried out on such images.

The X-ray emission from elliptical galaxies is mainly due to the thermal radiation from hot gas, with a smaller contribution from LMXBs. In the galaxies NGC 4472 and NGC 4649, the extended emission is symmetric relative to the galactic center (Fig.1) and no obvious manifestations of the galactic nuclear activity are observed, with the exception of a small displacement of the gas centroid in NGC 4472 to the north from the optical center of the galaxy.

Our subsequent analysis is performed in the energy ranges 0.2–0.6, 0.6–1.2, 1.2–2.5 and 2.5–10 keV. These energy bands approximately bracket the different emission mechanisms in the interstellar gas. In the first and third bands, bremsstrahlung and free–bound transitions mainly contribute to the gas radiation. In the second range, bound–bound transitions on ions of heavy elements mainly contribute to the spectrum. The bulk of the interstellar gas radiation at a temperature  $T \sim 1$  keV is in the 0.6–1.2 keV band. In the fourth range, 2.5–10 keV, there is virtually no interstellar gas radiation.

Inspection of the images reveal faint, soft (detectable only in the 0.2–0.6 keV band) X-ray sources near the centers of

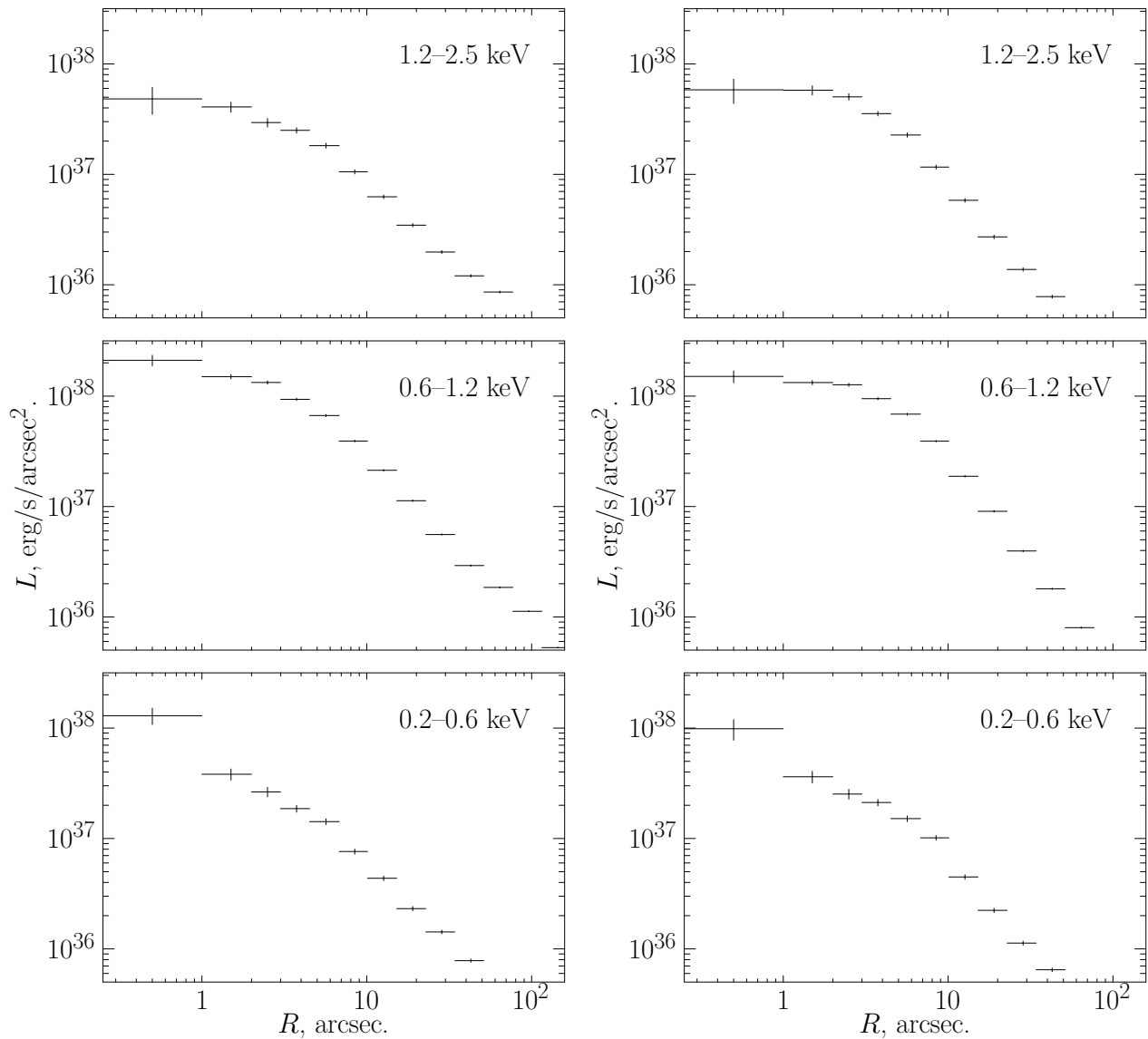
both galaxies (Fig. 1-2). Their angular sizes are consistent with the *Chandra* PSF at these energies,  $\sim 1''$ . In the 0.6–1.2 and 1.2–2.5 keV energy bands, the compact emission from the center is undetectable and the surface brightness profiles are well described by the  $\beta$ -model (Cavaliere & Fusco-Femiano 1976):

$$I(r) = \frac{I_0}{(1 + r^2/a^2)^{3\beta-0.5}} \quad (1)$$

with a  $\sim 5''$  core.

The most natural explanation of the central sources is the emission from the central supermassive black hole. We also considered, however, alternative explanations. For example, there may be power-law density peaks in the ISM distribution and the observed sources is in fact a thermal emission from the ISM. In this case, the absence of a central peak in the 0.6–1.2 keV band which is dominated by the line emission could be explained by the resonant scattering (Gilfanov, Sunyaev & Churazov 1987). However, this assumption can be rejected, because no central peak is observed in the 1.2–2.5 keV brightness profile, where the contribution from the line emission is small.

To verify the absence of any systematic offset between the optical and X-ray positions, we used other point X-ray source in the field. In general, point X-ray sources in elliptical galaxies are LMXBs, a considerable fraction of which are located in globular clusters. For instance, in one of the galaxies studied, NGC 4472, about 40% of the point X-ray sources are associated with globular clusters (Kundu et al. 2002). Comparison of the optical HST images and X-ray



**Fig. 2.** Surface brightness profiles for the galaxies NGC 4472 (left) and NGC 4649 (right) in the energy ranges 0.2–0.6, 0.6–1.2 and 1.2–2.5 keV.

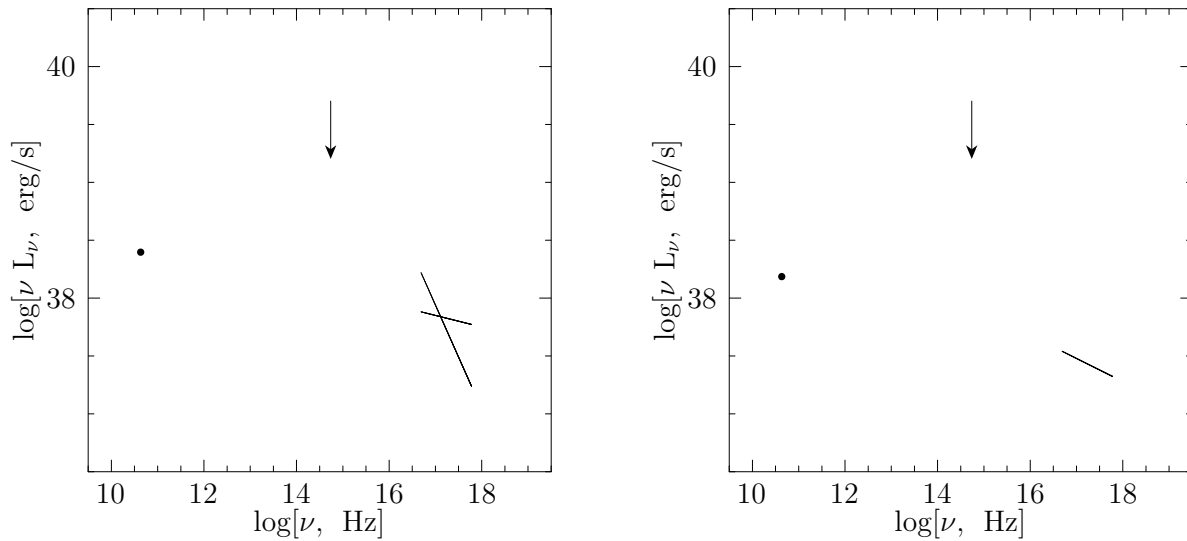
source locations shows the validity of the X-ray aspect solution to within  $1''$ . Our central X-ray sources coincide with the optical galaxy centroids to the same accuracy. This is the clearest indication for association of the detected sources with the galaxy nuclei.

#### THE SOURCE LUMINOSITIES

The observed flux from the central sources themselves is low. In the 0.2–0.6 keV band,  $22_{-7}^{+6}$  events were detected for the NGC 4472 source and  $11_{+6}^{-5}$  events for NGC 4649 (68% confidence interval estimated following Gehrels 1986). In both cases, the statistical significance of the detection is greater than  $3\sigma$ . In the 0.6–2.5 keV band, the flux is statistically significant at a  $3\sigma$  level only for NGC 4472 and is  $29_{+12}^{-11}$  photons. In the 2.5–10 keV band the total flux from

the entire central  $1''$  region in the galaxies is only a few photons.

A low flux from the sources does not allow an accurate judgment about their spectra to be made. Therefore, we used the power-law model to convert observed counts to the source luminosities. The results are presented in Table 1; in our calculations, the distance to the two galaxies was assumed to be 15.3 Mpc (Faber et al. 1997). If the ratio of the 0.6–2.5 and 0.2–0.6-keV fluxes is described by an effective power-law slope, then we obtain the following photon indices:  $2.5 \pm 0.4$  for NGC 4472 and  $> 2.2$  for NGC 4649. Figure 3 shows the power-law models with the derived parameters of the photon index and, for comparison, the source radio luminosities at a frequency of  $4.3 \times 10^{10}$  Hz and the upper limits on the optical flux at  $5.45 \times 10^{14}$  Hz taken from



**Fig. 3.** Radio (dots) and X-ray (lines) fluxes from the central sources in the galaxies NGC4472 (left) and NGC4649(right) and upper limits on the optical luminosity (arrows)

**Table 1.** Luminosities of the central sources

Object	$L_{0.2-0.6}, 10^{37} \text{ erg/s}$	$L_{0.6-2.5}, 10^{37} \text{ erg/s}$	$L_{2.5-10.0}, 10^{37} \text{ erg/s}$
NGC4472 ..	$9.2^{+2.8}_{-2.4}$	$7.3^{+2.9}_{-2.6}$	$< 3.4$
NGC4649 ..	$6.0^{+3.2}_{-2.6}$	$< 3.4$	$4.6^{+4.7}_{-3.1}$

Di Matteo et al.(1999).

In conclusion, we can give the interstellar-gas parameters required to estimate the accretion rate. The gas density at the galactic centers can be determined by using model (1) for the galactic-gas surface brightness and by describing its spectrum by the mekal model of radiation from an optically thin plasma (Mewe et al. 1985; Kaastra 1992; Liedahl et al. 1995) in the XSPEC code [for details see Voevodkin et al. 2002]. Our calculations yield the gas densities  $\rho_g = (1.0 \pm 0.1) \times 10^{-24} \text{ g cm}^{-3}$  at the center of NGC 4472 and  $\rho_g = (1.1 \pm 0.1) \times 10^{-24} \text{ g cm}^{-3}$  at the center of NGC 4649. The gas temperature within  $2''$  is  $0.66 \pm 0.02 \text{ keV}$  in NGC 4472 and  $0.86 \pm 0.02 \text{ keV}$  in NGC 4649.

### CONCLUSIONS

We have analyzed the data on the elliptical galaxies NGC 4649 and NGC 4472 that have recently been obtained with Chandra and detected faint, soft X-ray sources at their centers. The most plausible interpretation of the luminosities of these sources is activity of a supermassive black holes. Note that the spectra of the central sources are considerably softer than those for most of the other objects in the field. How-

ever, we cannot completely rule out the interpretation of the observed central sources as being the radiation from binary systems of stellar mass.

If our sources indeed represent the emission from the central black holes, our results is the first X-ray detection of such systems in the quiescent state. In this case, the X-ray data on these galaxies should be useful for testing theories that explain the deficit of luminosity in the nuclei of many galaxies.

### ACKNOWLEDGMENTS

This work was supported by the Russian Foundation for Basic Research (project no. 00-02-17124) and by the “Young Scientist” program of the Russian Academy of Sciences.

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